**Microphysical Properties of Colorado Winter Storms
Deduced from Video Disdrometer Observations**

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1. Introduction

In order to improve the quantification of winter precipitation, discriminate among hydrometeor types, predict precipitation-impacted visibility, and develop algorithms for determining particle size distributions with remote sensors such as polarimetric radar the characteristics of hydrometeor distributions must be known. Observations of frozen and liquid particle distributions are also required for improving microphysical parameterizations in numerical forecast models.

In this report hydrometeor distributions obtained in Colorado with a video disdrometer during two winter seasons are described. The data are being used to find inter-relationships among particle size distribution (PSD) parameters and to verify that polarimetric radar can discriminate among hydrometeor types. [Computations of radar variables derived from disdrometer observations and polarimetric radar measurements are presented in an accompanying report entitled *Winter storm studies: Comparison of observations from a 2-D video disdrometer and polarimetric radar*.] We begin with a description of the disdrometer measurements and analysis procedures. Findings and implications are then discussed.

2. Data and analysis

A detailed description of the disdrometer used in this report is given by Kruger and Krajewski (2002). The disdrometer provides front and side views of hydrometeors falling through a 10 × 10 cm viewing area. Resolution of detected hydrometeors is roughly 0.15 mm in the horizontal. The vertical resolution depends on the hydrometeor terminal velocity and is roughly 0.1 mm for raindrops and 0.03 mm for snowflakes. While this limits the accurate determination of hydrometeor characteristics to particles with dimensions <0.6 mm, it is not overly restrictive for our purposes because radar measurements principally respond to the larger particles within the measurement volume. Information obtained includes hydrometeor silhouette images, equivalent volume diameter, maximum width and height, an estimate of oblateness (for raindrops), and terminal velocity.

The disdrometer was operated at the base of the Rocky Mountain foothills near NCAR during the 2002−2003 and 2003−2004 winters. Other instrumentation included thermometers, a hygrometer, anemometers, and heated rain gauges. Detected precipitation was predominantly orographic and stratiform. Often precipitation began as light rain which changed to snow as the lower atmosphere cooled by melting and evaporation. Disdrometer measurements are subject to wind problems (Nešpor et al. 2000) which are exacerbated for snow by small terminal velocities. Wind-affected observations are readily identified by the distribution of hydrometers within the viewing region. To minimize potential problems the disdrometer was placed inside a wind shield. Analysis was restricted to those portions of events with *ambient* wind speeds of less than 2 m s^{-1}. Several hundreds of hours of disdrometer observations from winter storms have been collected. The dataset consists of relatively warm events with temperatures above -10^{o}C.

Particle distributions were fit with the gamma model (Ulbrich 1983)

$$N(D)=N_0 D^{\mu}\exp(-\Lambda D) \quad , \qquad (1)$$

where N_0 (units of $\mathrm{mm}^{-\mu-1}\ \mathrm{m}^{-3}$) is a number concentration parameter, μ is a distribution shape parameter, Λ (mm^{-1}) is a slope term related to the larger particles, and D (mm) is the particle equivalent volume diameter. The three governing parameters in (1) were computed from the 2nd, 4th, and 6th moments of the observed size distributions. Distributions were computed for 5-min samples. Typically, each sample contained hundreds of particles. Snowflake volumes were computed by revolving the silhouette images from the two disdrometer channels and then finding the geometric mean. Estimates of snow density were computed from the total volume of precipitation as estimated with the disdrometer and the precipitation mass as determined with rain gauges. Particle habits can be determined from shape and terminal velocity information. However, in this analysis a careful attempt to segregate events, for example, as characterized by snowflakes or snow pellets, has not been made.

3. Observations and findings

A time series of observations and derived precipitation properties for a cold-frontal snow event on 25 January 2004 is illustrated in Fig. 1. Temperatures fell and the relative humidity rose with the onset of light snow at the disdrometer site (~2247 UTC). The precipitation caused a significant decrease in visibility. [The visibility plot is scaled to show the larger variation rather than the detailed response to changes in precipitation characteristics.] An increase in median particle diameter (D_0) during heavy precipitation is apparent. Also, there is a tendency for heavier precipitation to associate with $\mu < 0$. PSDs with negative shape factors typically exhibit small numbers of large aggregates and super-exponential numbers of small ice particles.

Observed relationships between PSD attributes and temperature are shown in Fig. 2. Each dot represents a 5-min sample; each asterisk represents a longer time period during which particle habits were relatively constant. Figure 2a shows little temperature influence on hydrometeor size (D_0) until temperatures warm above -4^{o}C. This is

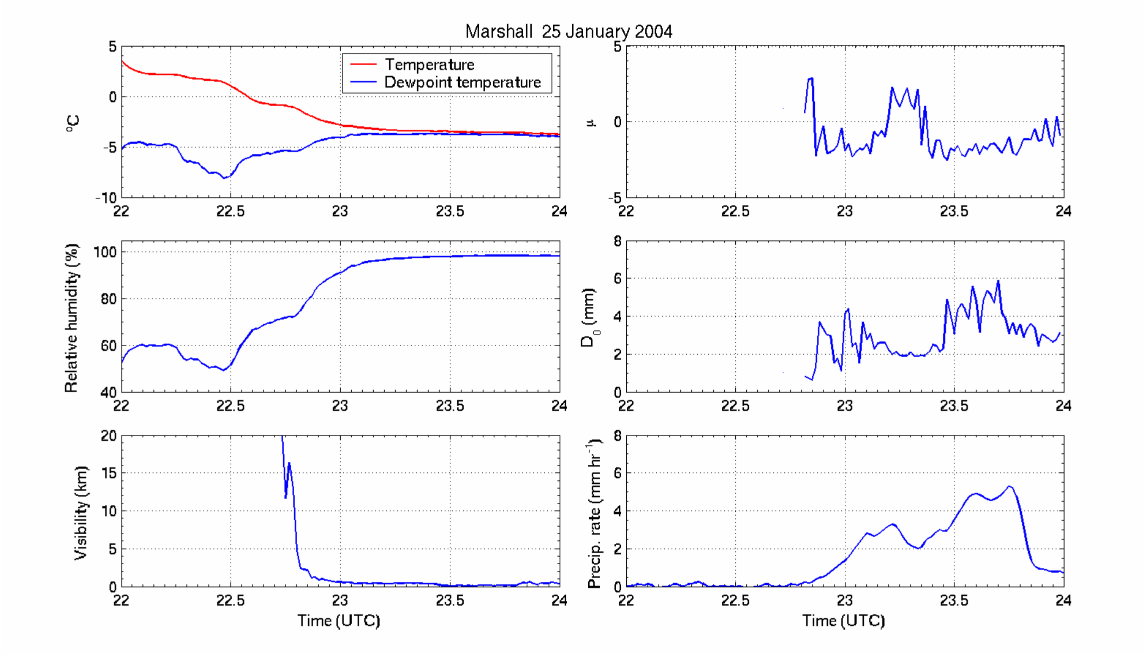

FIG. 1: Time series of precipitation characteristics and environmental variables as determined from disdrometer observations and other sensors.

approximately the temperature at which particle stickiness increases and aggregation is enhanced (Hosler et al. 1957). Note that the three longer time periods with the largest D_0s occur at temperatures above −4°C. On the other hand, for some events D_0 remains small (~2 mm). Hosler et al. determined that aggregation is suppressed if the vapor pressure is not ice saturated.

Mean volume-weighed particle terminal velocity and temperature are positively correlated (Fig. 2b). For cold snows (−10°C), velocities are slightly less than 1 m s^{-1}. Velocities increase to about 1.3 m s^{-1} at 0°C. The largest departure from the mean trend is for an event at −4°C that was dominated by snow pellets. All else being equal, a 30% increase in terminal velocity would have a significant impact on snow accumulation.

Relationships between temperature and μ and the PSD slope parameter Λ are presented in Figs. 2c and 2d. There is little correlation. Compared to rain, distribution shape factors for snow are small (mostly −2 to 2), suggesting that PSDs are approximately exponential (μ = 0) for many events. Negative μs are common when there is significant aggregation. The most significant outlier in Figs. 2c and 2d is the storm dominated by snow pellets. The absence of a relationship between temperature and the PSD slope contradicts a similar study conducted by Houze et al. (1979) who found a moderate correlation (−0.66).

The dataset is small, but particle concentration parameters (N_0) show a general increase as temperatures warm to −4°C (Fig. 2e). Ice particle replication may be occurring. At higher temperatures the concentration parameter systematically decreases. Because D_0s are increasing and Λ is decreasing on average, the reduction in N_0 is probably a consequence of aggregation. Our N_0s roughly match magnitudes found by Houze et al. However, Houze et al. determined that N_0, computed from the larger particles in observed PSDs, decreased over the entire temperature range of −50°C to

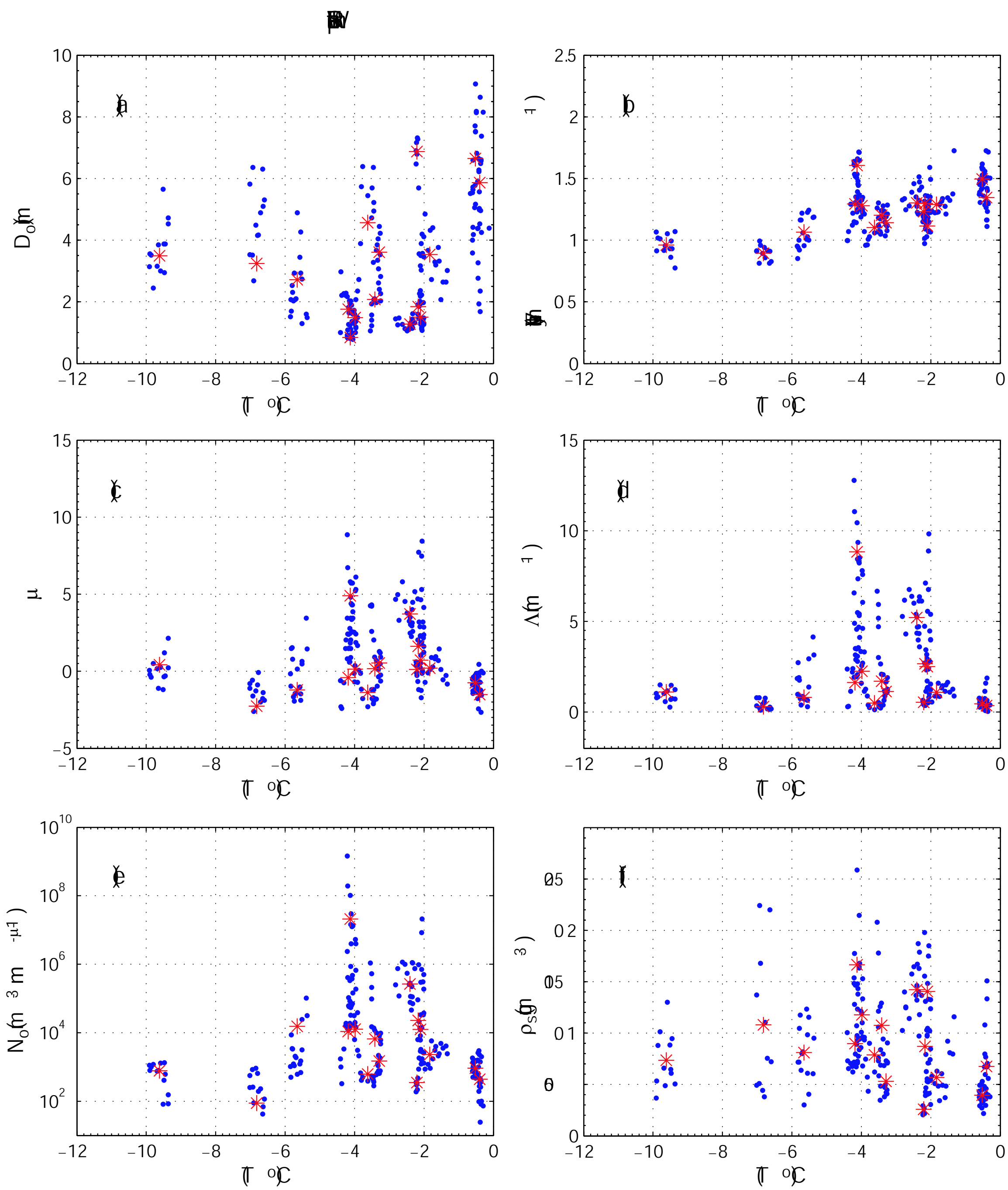

FIG. 2: Attributes of particle size distributions in winter storms, as determined from disdrometer observations, plotted against ambient temperature.

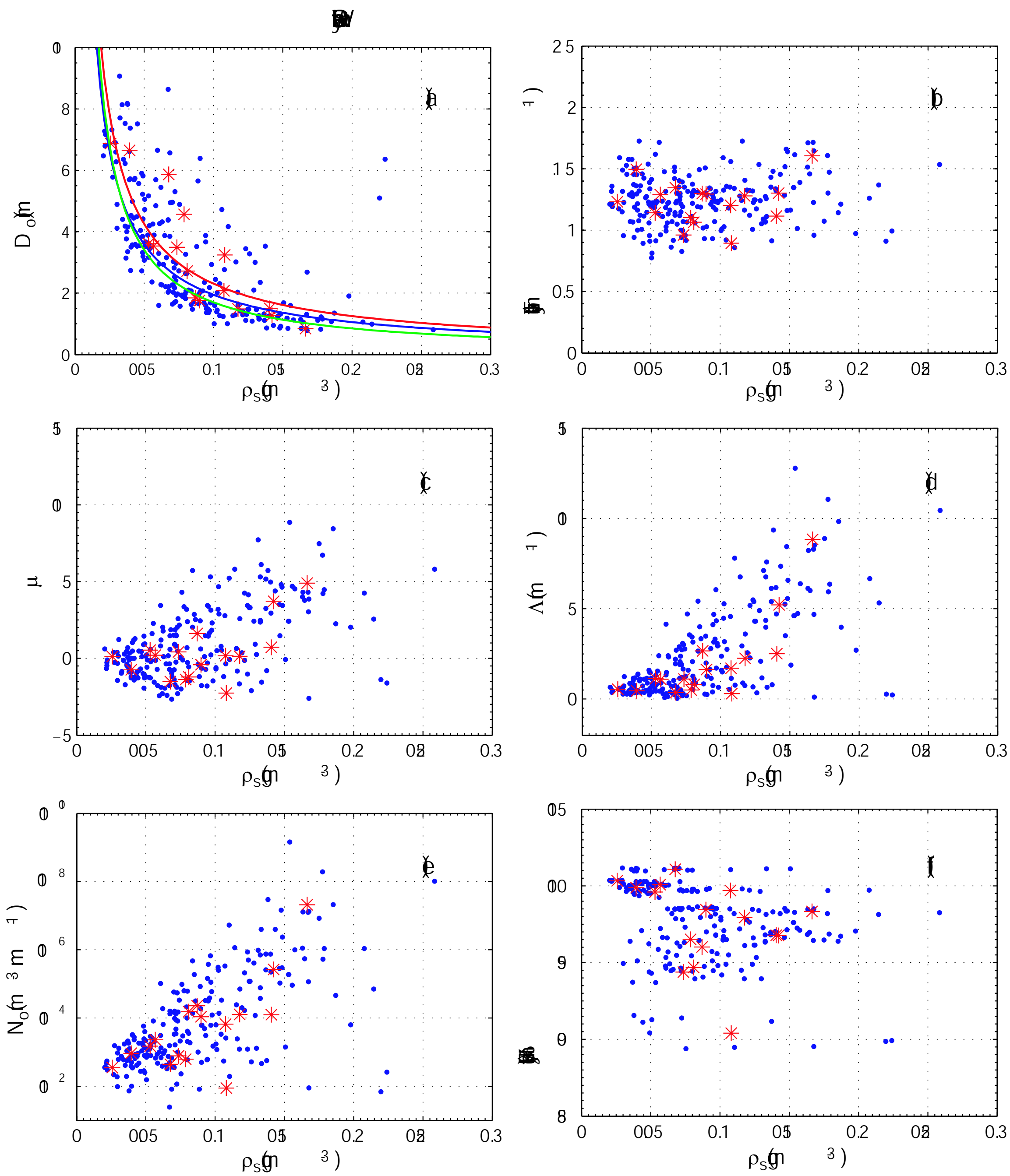

FIG. 3: Relationships between particle bulk density and size distribution attributes (a−e) and the relation with ambient relative humidity (f).

10^{o}C. The correlation was −0.90. This result has been widely used by the numerical forecast community because, if true, it simplifies the treatment hydrometeors in numerical models. Although the temperature range is narrow, the fact that our data does not support the Houze et al. study is cause for concern.

The correlation between temperature and snow bulk density (ρ_s) is depicted in Fig. 2f. The distribution is noisy with little or no correlation. The spread in particle density is greatest with temperatures of −4^{o}C to −2^{o}C. Higher densities are likely characterized by snow pellets and heavily rimed hydrometeors, whereas low densities associate with aggregates.

Correlations between PSD attributes and mean bulk density are presented in Fig. 3 (panels a−e). Figure 3a shows the relationship with median volume diameter. The green curve was found by Holroyd (1971) for Great Lakes snow storms. The blue curve is a least-squares fit to the 5-min samples, and the red curve is a fit to the longer time periods with common hydrometeors. Particle density and median volume diameter are inversely related. Large fluffy aggregates have low density. Smaller particles tend to be characterized by more pristine ice crystals or ice pellets and are relatively dense. Radar measurements and estimated snowfall rates are sensitive to assumptions regarding particle size and bulk density. Improved estimates of snowfall rate should be possible by relating radar reflectivity to mean particle size and accounting for changes in bulk density.

Except for the snow pellet event, there is a slight tendency for the mean particle terminal velocity to increase as particle density decreases (Fig. 3b). Large low-density aggregates typically have somewhat larger terminal velocities than smaller particles. Low density and large terminal velocity seems counterintuitive. The explanation seems connected with particle size in that larger particles commonly have higher terminal velocities. Similar relationships exist for raindrops and hailstones.

The PSD governing parameters (μ, Λ, and N_0) all show a tendency to increase as the snow bulk density increases—at least for statistics computed for the longer time periods (Figs. 3c−e). Although it is not shown here, smaller parameter values occur with heavier precipitation rates. There is correlation between snow density and relative humidity (Fig. 3f). Time segments with the lowest densities generally represent high humidity (and warmer) events in which aggregation is significant.

The relationship between the PSD shape factor and slope is depicted in Fig. 4 for snow, rain, and mixed-phase precipitation. Snowfalls (Fig. 4a) have small μ, i.e., particle distributions are often close to exponential or super-exponential. Raindrop size distributions for these winter storms show a wide range of shape factors (Fig. 4b), indicating the distributions are typically more narrow than that for snow. The wider distribution of data points probably relates to the degree of aggregation in the melting layer. The plotted curve is the $\mu - \Lambda$ relation found by Brandes et al. (2003) for subtropical (Florida) rains. The distribution for winter rain in Colorado seems more linear and has a near constant slope. This undoubtedly follows from the slope of the snow particle distributions in the overlying snow region (Fig. 4a). Nevertheless, our results suggest a physical relationship between these two parameters. The dataset for mixed-phase precipitation (Fig. 4c) is relatively small but indicates a distribution intermediate between snow and rain.

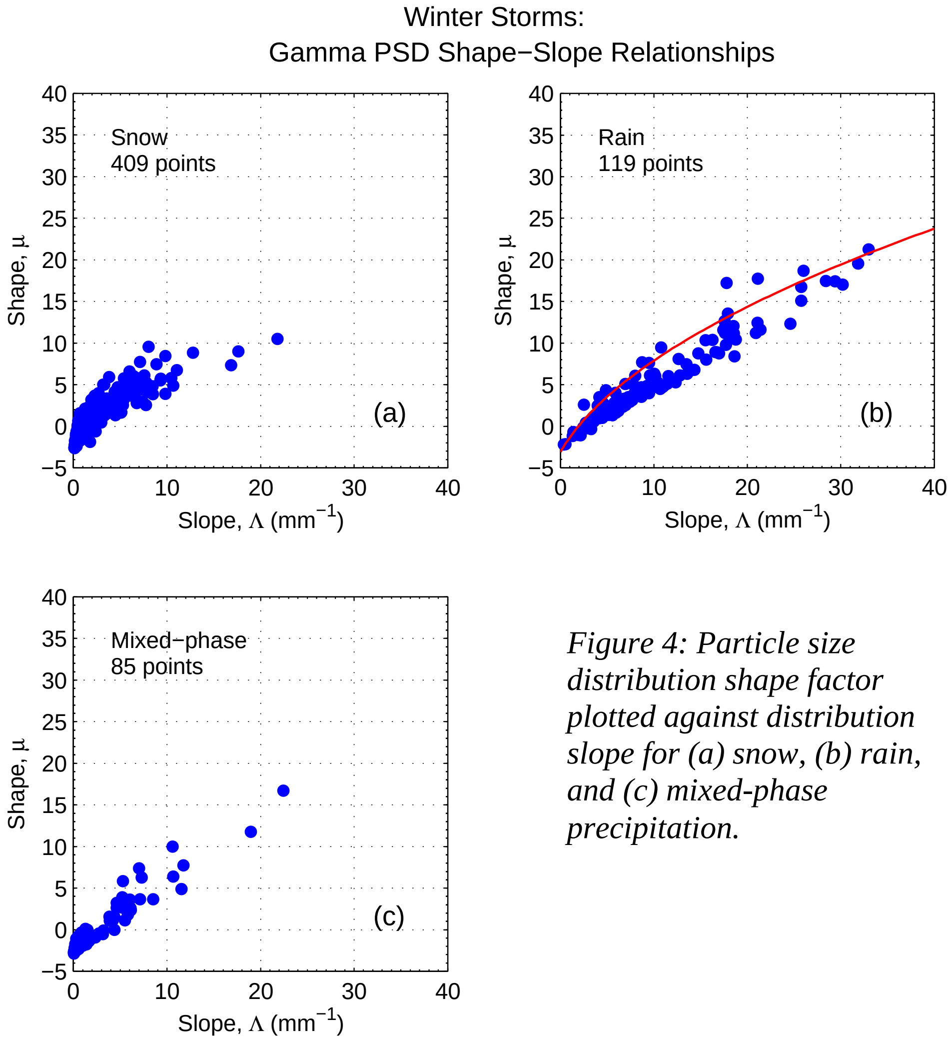

Figure 4: Particle size distribution shape factor plotted against distribution slope for (a) snow, (b) rain, and (c) mixed-phase precipitation.

4. Summary and discussion

The determination of inter-relationships among attributes of particle distributions in winter storms and their dependence on environmental factors such as temperature and humidity is important for interpreting polarimetric radar measurements and for developing algorithms that quantify snowfall and "predict" airport terminal visibility. The observations are also important for verifying radar-designated hydrometeor classifications and microphysical parameterizations in numerical forecast models.

Useful relationships uncovered so far include those between snow mean terminal velocity and temperature, between particle bulk density and median volume diameter, and between the shape and slope terms of the particle size distribution. Whether or not other useful relationships exist, for example, between μ, Λ, N_0 and temperature or bulk density, await the examination of additional dataset sets, particularly in colder regimes.

Relationships between μ and Λ are important because they effectively reduce the three-parameter gamma distribution [Eq. (1)] to two parameters and improve prospects of retrieving the PSD governing parameters from radar observations in that only two independent radar measurements are needed. Consequently, it should not be necessary to impose severe assumptions such as a constant μ or to compute Λ from a poorly defined relationship between Λ and temperature. If the PSD can be retrieved from polarimetric radar measurements, it should be possible to improve the quantification of winter precipitation with radar and estimate visibility. Efforts to show that radar measurements (reflectivity and differential reflectivity in particular) relate to winter precipitation characteristics at ground are described in the accompanying report.

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